Using *STEREO-B* as an L5 Space Weather Pathfinder Mission

[By D. F. Webb[1], D. A. Biesecker[2], N. Gopalswamy[3], O. C. St. Cyr[3], J. M. Davila[3], C. J. Eyles[4], B. J. Thompson[3], K. D. C. Simunac[5] and J. C. Johnston[6]]

[1] Institute for Scientific Research, Boston College, Chestnut Hill, MA, USA
[2] NOAA Space Weather Prediction Center, Boulder, CO, USA
[3] NASA Goddard Spaceflight Center, Greenbelt, MD, USA
[4] Space Science and Technology Dept., STFC Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, UK and Universidad de Valencia, Valencia, Spain
[5] Space Science Center, University of New Hampshire, Durham, NH, USA
[6] Air Force Research Laboratory, Battlespace Environment Division, Hanscom AFB, MA, USA
Correspondence to: D. F. Webb (david.webb.ctr@hanscom.af.mil)

The two *STEREO* spacecraft (Kaiser *et al.* 2008) were launched in October 2006 into near-1 AU solar orbits with *STEREO-A (*Ahead) leading and *STEREO-B* (Behind) trailing the Earth, each drifting away from the Earth at 22.5° per year. A special configuration of space weather interest occurred in October 2009 when *STEREO-B* arrived at the L5 Lagrange point which is located 60° east of the Sun-Earth line. Observations at or near this location permit use of *STEREO-B* as a pathfinder for a space weather monitoring mission (Akioka *et al.* 2005, Biesecker *et al*. 2008) that could include heliospheric imaging capabilities. In particular, the speed and size of an Earth-directed coronal mass ejection (CME) can be better determined from a side view than a head-on view. In addition, active regions and coronal holes can be viewed before they arrive on the Earth-facing disk, and their location, size and activity assessed. Finally, the geoeffective space weather resulting from high speed solar wind streams, such as radiation belt relativistic electron enhancements, can be forecast days in advance. Forecasting the hazardous effects of CMEs and solar wind streams is very important for protecting space assets, maintaining stable communication and surveillance systems, as well as protecting ground power grids (e.g., Bothmer & Daglis 2007).

The Sun-Earth Lagrange points mark positions where the combined gravitational pull of the two large masses of the Sun and Earth precisely equals the centripetal force required to rotate with them. Josef Lagrange, an 18th-century mathematician, proved that there are five such ‘gravitational wells’ in the Sun-Earth system located as shown in Figure 1. Of the five Sun/Earth Lagrange points, three are unstable and two are stable. The stable Lagrange points, L4 and L5, form the apexes of two equilateral triangles that have the large masses at their common vertices. The instabilities at the L1 and L2 points, Sunward and anti-Sunward of Earth, have slow enough decay rates that spacecraft placed there need only small, periodic orbit corrections. Currently there are three solar wind spacecraft at L1, *ACE*, *SOHO* and *Wind*, and several astrophysical spacecraft at L2. Although in principle the L4 and L5 points are gravitationally stable, the potential wells are very wide and shallow so that external influences, such as the gravitational influence of Jupiter, are significant. Consequently, orbit corrections will still be required to maintain a spacecraft reasonably close to L5.

STEREO-A reached the L4 point in September 2009 and *STEREO-B* reached L5 in October 2009. Using some recent studies as examples, we describe three important ways that the *STEREO-B* observations in the vicinity of L5 can be used to support the development of a space weather monitoring mission: tracking CMEs, solar activity, and solar energetic particle events.

Tracking Earthbound CMEs

A monitor placed at L5 (or L4, or preferably at both locations) would be ideal

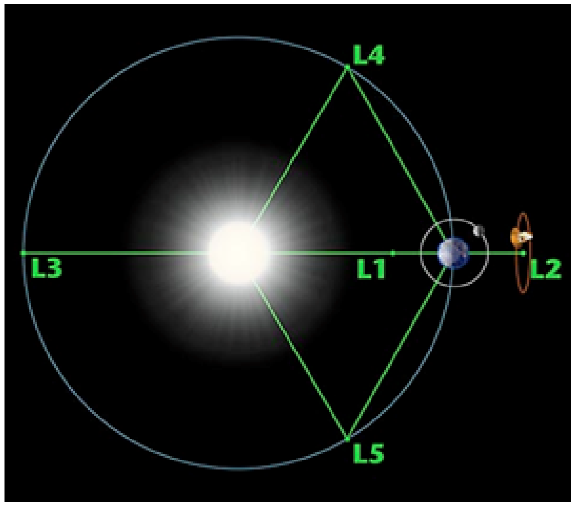

Figure 1. Lagrange points of the Sun-Earth system in the ecliptic plane. The L4 (L5) point leads (trails) the Earth in its orbit. From Neil J. Cornish, WMAP's (Wilkinson Microwave Anisotropy Probe) Education and Outreach Program: http://map.gsfc.nasa.gov/mission/observatory_l2.html. The larger and faster an Earthward-bound CME, the more likely it is to be geoeffective and create a storm of longer duration. (Knowing the magnetic field within the CME is also important, but currently this can only be measured, with little warning time, at L1.)

for viewing and studying CMEs aimed Earthward.

The predicted arrival of a CME at Earth based upon observations from L5 could be directly checked with *in situ* data at L1, currently provided by *ACE*, *SOHO* and *Wind*. Because of the longitude ambiguity inherent from using a single imager viewpoint, L5 remote imager views of interplanetary CMEs would be significantly more valuable in conjunction with Earth-based CME images. The most important space weather parameters that can be estimated by remote viewing of an Earthward CME are its forecasted time of arrival, the trajectory of its central axis, and its size or volume. The larger and faster an Earth-directed CME, the more likely it is to be geoeffective and create a storm of longer duration. (Knowing the magnetic field within the CME is also important, but currently this can only be measured, with little warning time, at L1.)

The different vantage points from L5 and Earth permit us to determine the velocity vector of the CME and thus predict its arrival time, as well as the distribution of plasma that might impact Earth. The kinematics of the CME could be determined by means of triangulation techniques, such as are being used with simultaneous *STEREO* image pairs. For example, imaging observations at L5 minimize the distance ambiguity inherent in 'halo' observations, as CMEs can be viewed 'edge-on', with clear wave front profiles (e.g., Wood *et al.* 2009).

With *STEREO-B* as a pathfinder, we are now able to compare *STEREO* SECCHI (Howard *et al.* 2008) Heliospheric Imager (HI – Eyles *et al.* 2009) views of inter-planetary CMEs with those from the Solar Mass Ejection Imager (SMEI – Eyles *et al.* 2003) in Earth orbit (e.g., Webb *et al.* 2009*a*, Howard & Tappin 2009*b*). Since the *STEREO* HI imagers view any CME travelling along the Sun-Earth line in opposing off-centre projections, image reconstruction permits the determination of the CME's trajectory, velocity, geometry/ size and density distribution.

The L5 (and L4) location is ideal for imaging Earthward CMEs in the inner heliosphere since their white light brightness is minimally affected by Thomson scattering considerations. The intensity of Thomson

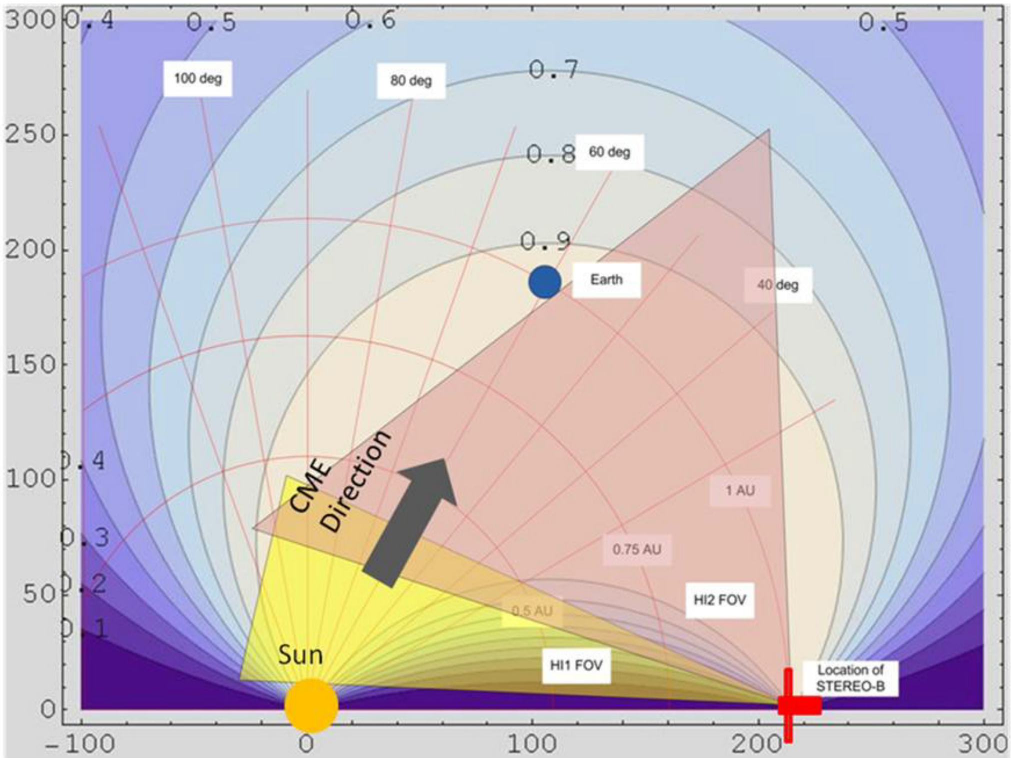

Figure 2. Diagram showing that the effect on the white light brightness from Thomson scattering of an Earth-directed CME viewed from *STEREO-B* at L5 will be minimal. The yellow and beige areas represent the fields of view of the HI-1 and Hi-2 instruments, respectively, on *STEREO-B* when it is 60° from the Sun-Earth line. The arrow represents an Earth-directed CME. The banana-shaped segments denote the Thomson scattering surfaces that diminish the brightness by 0.9, 0.8, etc. The ordinates are in units of solar radii.

scattering of visible sunlight has a maximum where the distance from the Sun to the line-of-sight is a minimum (Vourlidas & Howard 2006, Howard & Tappin 2009*a*), but the distribution is broad. Figure 2 shows a contour plot of the Thomson-scattered contribution as a fraction of the peak intensity for lines-of-sight from L5.

The tracking process is illustrated by a Sun-to-Earth event in December 2008 (Davis *et al*. 2009). The event began with an eruptive prominence and coronal arcade in the northern solar hemisphere on 12 December 2008. Images from the *SOHO* LASCO and *STEREO* SECCHI instruments suggested that the associated CME was directed towards Earth (Figure 3). The CME was later imaged by HI-A and –B and SMEI as it propagated outward and then *in situ* at the *ACE* spacecraft at L1. The HI images showed three density fronts that were predicted to arrive at *ACE* and then confirmed as CME plasma signatures. However, the CME was only modestly geoeffective, likely because most of its material passed north of the ecliptic plane as observed, for example, by SMEI. Despite *STEREO* – Earth separations of only 45° for this event and given adequate data latency, *STEREO* could have provided early warning of CME impact at least 24 hours in advance. (A similar average warning time was derived for CMEs driving major storms using LASCO and SMEI imaging [Webb *et al.* 2009*b*]). Observations of Earth-directed CMEs from the L5 region will improve the error in predicting CME arrival time since the longitudinal portion of the leading edge destined to hit Earth will be more closely tracked. We are currently in the rise of activity cycle 24 during which we expect the

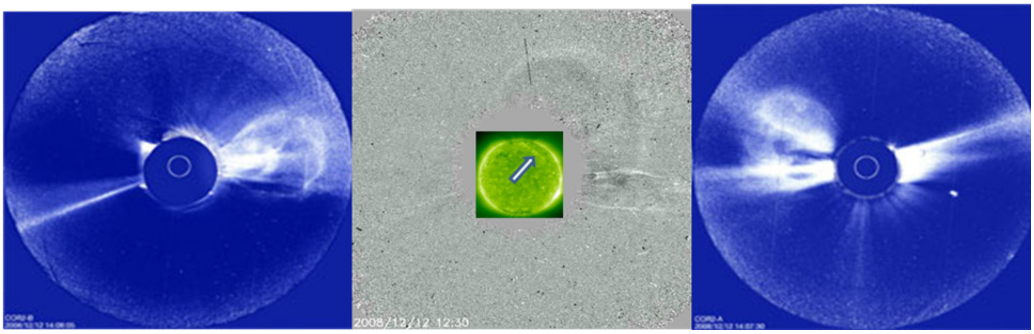

Figure 3. *STEREO* COR-B/COR-A image pair showing the CME off the west (left) and east (right) limb, respectively, and from *SOHO* at L1 (centre). A LASCO C2 running difference image is shown with an EIT image showing the event arcade (arrow). The LASCO image shows a faint partial halo (~180°) mostly to the north and west. [The *STEREO* COR images are from NASA.]

occurrence and size of CMEs to increase. To date, however, there have been only three to four additional small CMEs that were Earth-directed.

Solar Activity and Corotating Stream Interactions Regions

In the L5 vicinity, *STEREO-B* observes the solar hemisphere beyond the Earth-facing east limb, permitting detection of developing active regions and coronal holes. These observations, in turn, can be used to produce advanced forecasts of events such as flares, CMEs and high speed streams detected both by remote viewing and *in situ* measurements before they reach Earth.

Corotating stream Interactions Regions (CIRs) form when high-speed solar wind streams emanating from coronal holes overtake existing slower wind streams, leading to plasma compression and enhanced magnetic fields. CIRs can be geoeffective because of the resulting enhanced total, B, and southward, B_s, magnetic fields, which can yield overall energy inputs during geomagnetic storms equivalent to those from CMEs (e.g., Turner *et al.* 2009, Borovsky & Denton 2006).

To predict the arrival and geo-effectiveness of CIRs at the Earth, we need to detect and track the source coronal holes, track the CIRs through the heliosphere, and sample the plasma and magnetic fields *in situ*. *STEREO-B* is now being used for all these tasks.

A relatively strong CIR pattern was apparent since the launch of *STEREO* as a two-stream recurrent structure through the end of 2008 (Mason *et al*. 2009). Simunac (2009*a*, *b*) validated the usefulness of an L5 solar wind monitor by comparing observations of CIR crossings at *STEREO-B* and *-A* (Figure 4, left) when they were 60° apart, the same angular distance as between L5 and the Earth. Figure 4 (right) shows results for a strong CIR in July 2008 using measured bulk solar wind speeds at *STEREO-B* to predict the wind speeds at *STEREO-A*. Simunac et al. (2009*b*) conducted a similar study using data collected between March 2007 and February 2008 when the separations between the *STEREO* spacecraft were <45° in heliographic longitude. 70% of the interfaces between slow and fast solar wind arrived earlier than predicted at *STEREO-A*, consistent with an observed westward drift of the coronal holes.

The NOAA SWPC (Space Weather Prediction Center) has multi-day *STEREO-B* plots of plasma data showing the time that a co-rotating structure would take to arrive at *ACE* (see www.swpc.noaa.gov/stereo/mag_plastic_B_24h_w.html, for example).

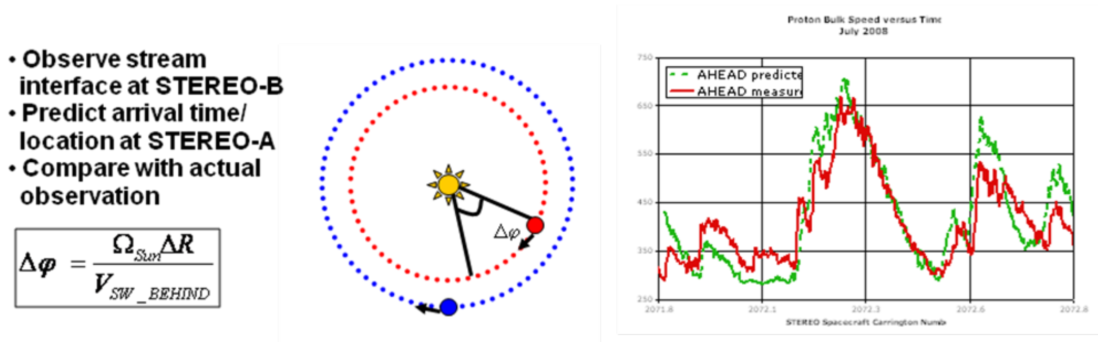

Figure 4. Procedure (left) and results (right) using *STEREO-B* solar wind speed data to predict the wind speed at *STEREO-A* (green) compared to the actual measured speed (red).

The predicted time of arrival is based on the angular separation, radial distance, and the most recent solar wind speed observed at *STEREO-B*. Near real-time *STEREO-B in situ* magnetic field and solar wind observations are used to predict the wind conditions at L1/Earth. The SWPC also hosts sites where the Wang-Sheeley-Arge model (Arge & Pizzo 2000) is used to predict the solar wind speeds at *STEREO* (see http://helios.swpc.noaa.gov/WSA/STEREO/) and L1/ACE (www.swpc. noaa. gov/ws/) locations.

We can now image the inter-planetary density enhancements associated with CIRs using data from the HI instruments and SMEI (Sheeley *et al.* 2008*a*, *b*, Rouillard *et al.* 2008, Tappin & Howard 2009). These observations can give much longer advance warning times than using *in situ* observations alone. For example, Tappin and Howard showed that comparison of images with models of a CIR observed in November 2008 could be used to provide up to 10 days advance prediction of the CIR arrival at the Earth. In that study, the *in situ* observations alone gave a 3.2-day advance prediction from *STEREO-B* to ACE (43° separation angle), whereas at L5 these values increase to ~14 days for imaging and ~4.5 days for *in situ* observations.

Solar Energetic Particle Events

Solar energetic particle events (SEPs), originating from flares and CMEs, are among the most hazardous and difficult-to-predict aspects of space weather. The particles can arrive at 1 AU within tens of minutes of their production. *STEREO-B* is now well connected to open magnetic field lines near Sun centre as viewed from Earth. Since particles are constrained to travel along the Archimedean-spiral open field lines, for well-connected events the SEP onset is prompt with a rapid rise to the peak. Therefore, in the wide L5 region, *STEREO-B* is well connected to field lines emanating from near Sun centre or eastward as viewed from the Earth. The solar source locations of SEP-effective CMEs tend to occur at 70° W longitude and these CMEs have average speeds of ~1000 km s^{-1} (Gopalswamy *et al.* 2010). Thus, *STEREO*-B's particle detectors can help predict the onset time and size of a prompt SEP, as well as the arrival of the associated ICME, at Earth. As the observer moves towards the west (moving the ICME source location eastward), the onset of the SEP event is delayed and the rise time to its peak lengthens (see Cane & Lario 2006). In the L5 region, *STEREO-B* can detect SEPs even farther to the east, giving correspondingly longer prediction lead times. Thus, SEP observations at L5, combined with those at L1, permit studies of the temporal and longitudinal characteristics of individual events. Unfortunately, thus far no large SEPs have occurred since early in the *STEREO* mission to permit this testing.

An L5 Monitor

We have shown that observations from *STEREO-B* can be used as a pathfinder for a space weather mission in the L5 region. At the time of this writing (June 2010), the spacecraft has travelled beyond L5, and is ~70° east of the Sun-Earth line. Over the next year or so, these observations can continue to be used to demonstrate space weather applications, and we encourage studies that help demonstrate the enhanced space weather capabilities of an L5 mission. NOAA is developing instrument requirements for an L5 monitor, though at this time NOAA has no plans for such a mission. These preliminary requirements include measurements of the following parameters:

***Solar Wind**:* Magnetic field vector, plasma ion density, temperature and velocity, high energy electrons;

***Solar Imagery**:* X-ray, radiance, corona, heliosphere (white light), magnetograms; and medium and high energy *protons*.

One important aspect of an L5 mission could be the expanded longitudinal coverage of photospheric magnetic field measurements to provide improved inputs into potential field and other coronal models used for space weather predictions. Unfortunately, this cannot be tested with *STEREO-B* since it does not carry a magnetograph.

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About the Principal Author

David Webb is a research physicist studying solar CMEs and transient disturbances in the interplanetary medium, together with their effects at the Earth. He is also affiliated to the Air Force Research Laboratory, Center of Excellence in Space Weather, at Hanscom AFB, MA. In the 1970s and 1980s, Webb worked as a Senior Scientist in the Solar Physics Group at American Science and Engineering. He was a Visiting Scientist at the NCAR High Altitude Observatory in Boulder, CO, studying coronal dynamics. Currently, he is a Co-I on the Solar Mass Ejection Imager (SMEI), the *SOHO* LASCO, and the *STEREO* missions. He has used data from the *SMM*, *SOHO* and *STEREO* coronagraphs, *Helios*, the *Yohkoh* SXT and *SOHO* EIT imagers, and *Wind*, *ACE* and *Ulysses* to study the solar sources of and heliospheric propagation of CMEs and shocks and their geophysical consequences. He has published over 130 scientific papers. Webb has led research studies establishing the link between halo CMEs and geomagnetic disturbances. He was on the steering committees for SHINE, the Int. Solar Cycle Study, as well as the SHINE-GEM-CEDAR and S-RAMP 1999 Space Weather storm campaigns; he coordinated the SHINE Campaign Events studies. He is currently the coordinator of the *STEREO* Space Weather group. He was the coordinator of the IHY's Schools Programme and Newsletter, the IAU's Representative for IHY, and will be its representative for the ISWI. Webb is a member of the AAS and its Solar Physics Division, the APS, AGU, and IAU, having served the IAU as President of Division 2 and Commission 49.